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APPLICATIONS OF OPTICAL SIGNAL PROCESSING TO COMMUNICATIONS, CO--ETC(U)

AUG 78 F A HORRIGAN, W W STONER F19628-77-C-0110

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RADC-TR-78-180
Final Technical Report
August 1978

AD A058721

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APPLICATIONS OF OPTICAL SIGNAL PROCESSING TO COMMUNICATIONS, COMMAND, CONTROL

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18 19 **REPORT DOCUMENTATION PAGE** — READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER RADC-TR-78-180	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE (and Subtitle) APPLICATIONS OF OPTICAL SIGNAL PROCESSING TO COMMUNICATIONS, COMMAND AND CONTROL		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 25 Jan 77 - 25 Jan 78
		6. PERFORMING ORG. REPORT NUMBER SAI-77-511-BOS
7. AUTHOR(s) Frank A. Horrigan William W. Stoner		8. CONTRACT OR GRANT NUMBER(s) F19628-77-C-0110
9. PERFORMING ORGANIZATION NAME AND ADDRESS Science Applications, Incorporated 3 Preston Court Bedford MA 01730		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62702F 46001902
11. CONTROLLING OFFICE NAME AND ADDRESS Deputy for Electronic Technology (RADC/ESO) Hanscom AFB MA 01730		12. REPORT DATE August 1978
		13. NUMBER OF PAGES 46
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Same		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited. 12 53p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

RADC Project Engineer: William Miceli (ESO)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Spread Spectrum	Coherent Optics
Optical Processing	Noncoherent Optics
Direct Sequence Code	Synchronization

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report discusses the application of optical signal processing to synchronization and decoding of spread spectrum signals. Synchronization and decoding are first characterized as correlation operations. Three distinct optical correlation techniques are discussed in the context of spread spectrum requirements: brute force shadowcasting, noncoherent correlation via pupil masks, and conventional coherent optical matched filtering and correlation. The strong and weak points of each technique are identified. The noncoherent (Cont'd)

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pupil mask technique is novel, and hence requires deeper theoretical and experimental exploration. For future work, an experimental comparison which encompasses all three competing techniques is outlined.

EVALUATION

1. This is the Final Report of the contract. It covers research done during the period 25 Jan 77 through 24 Jan 78. The objective was to conduct a thorough assessment of the applicability of Optical Signal Processing (OSP) techniques to Air Force problems of Communication, Command and Control.

2. Criteria for the successful implementation of OSP related techniques were developed, and various C^3 related system requirements were identified. Optical processors can be exploited to perform two dimensional, real time spectral analysis, correlations, convolutions, frequency domain filtering and pattern recognition.

3. The above work is of value since it provides a capability to process high bandwidth/data rate signals in parallel via optical Fourier/Fresnel transformations at a minimum cost and size. This work will result in both new and improved signal processing devices applicable to radar, communications, speech processing and ECM/ECCM systems.

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APPLICATIONS OF OPTICAL SIGNAL PROCESSING TO COMMUNICATIONS, COMMAND AND CONTROL

1. SUMMARY

1.1 Objectives

The primary objective of this program is to conduct a thorough assessment of the applicability of Optical Signal Processing techniques to the Air Force problems of Communications Command and Control. The program includes the following tasks:

- An in-depth assessment of the present state of the art of coherent and incoherent optical signal processing techniques.

- Identification and analysis of specific promising applications of OSP to the handling of wide bandwidth radar and communication signal, with particular emphasis given to the incoherent techniques and the various hybrid combinations possible through the incorporation of SAW, CCD, and other analog technologies.

- Identification of the specific technical deficiencies which hinder the implementation of these applications.

- The recommendation of specific conceptual and experimental programs to resolve these deficiencies.

1.2 Conclusions

Although many other significant applications exist, the most attractive application of optical signal processing to C^3 lies in the area of spread spectrum communications. The spread spectrum problem of synchronization and decoding reduces to a correlation. Because of the speed-of-light, parallel processing capability of optics, correlation may in principle be performed more rapidly with optics than with electronics. Three distinct optical correlation techniques are examined: brute force shadow casting, noncoherent correlation via pupil masks, and conventional coherent optical matched filtering and correlation. The noncoherent pupil mask technique is novel, and hence demands deeper theoretical and experimental exploration.

2. OPTICAL SIGNAL PROCESSING

From a systems point of view, the most characteristic feature of an optical processor is that it is an analog device which employs a modulated beam of light; that is, the information is placed on an optical carrier. Since this modulation or input task can rarely be accomplished without great effort, particularly in applications requiring real time response, the natural question to ask is: Why bother? What advantages are to be gained from the use of an IF at optical frequencies? And when do the benefits outweigh the penalties?

Many of the potential advantages are directly traceable to the physical laws which govern the propagation of light. Because of the very short wavelengths, light beams can be conveniently constrained to very small cross sections with dimensions on the order of microns or less, permitting extremely compact two and three dimensional storage of information at densities of 10^{12} bits per cc or higher (i.e., approximately one bit per cubic micron). As an electromagnetic phenomena satisfying Maxwell's equations, light propagation is describable naturally as summations of elementary wavelets via Huygen's Principle which are formally identical to two dimensional Fourier or Fresnel transform relationships. Because of the high frequencies of optical waves ($\sim 10^{15}$ Hz) and the relatively weak frequency variation of its properties of interaction with matter, gigahertz bandwidth modulations are readily tolerated. And finally, the nature of its interaction with various materials permits light beams to be easily manipulated by simple and relatively inexpensive components such as lenses, mirrors, transparencies, gratings, and the like.

Thus by placing the information on an optical carrier one can hope to gain

- convenient 2 and 3D storage of large amounts of information,
- automatic parallel processing via propagation-associated Fourier/Fresnel transformations,
- high bandwidth/data rate capabilities, and
- simple physical components.

If the intended application does not exploit one or more of these advantages there is probably no reason to consider an optical processor for the job. If, on the other hand, the application appears to qualify, then one must pay careful attention to the obstacles and penalties which may be associated with an optical implementation. Chief among these is the simple fact that optical processors are analog devices and thus troubled by the low frequency alignment and level drifts which afflict all such systems. Of course, this in itself does not disqualify analog devices, but does become a critical factor if equivalent digital techniques exist. Next one must face the difficult modulation issues associated with impressing the information onto the optical carrier -- the input problem. A one dimensional time modulation of a light beam is a relatively simple task and bandwidths in excess of a GHz have been demonstrated a number of times using different light sources and different modulation techniques. However, to make maximum use of optical processing capabilities, it is usually necessary to impress on the beam information in the form of one or two dimensional spatial modulations of light amplitude and phase. To convert an incoming electrical signal to a one or two dimensional optical transparency in real or near-real time requires one of the many light valves currently under development.[(1)] With each comes problems of resolution, total capacity, dynamic range, noise, write and erase time, and so forth. All are limited in major ways and few are readily available.

While achieving the appropriate input modulation is notoriously difficult, the implementation of stored two dimensional transparency "filters" which operate on the incoming information is relatively easy. Although great care must be taken and the processing tolerances are often severe if high quality performance is required, frequently it is possible to generate these "filters" at our leisure making use of a variety of computer and photographic aids.

In terms of the generic strengths and weaknesses of optical processing we can establish the general features which should be characteristic of applications which can benefit significantly from an optical implementation. Not too surprisingly, since an optical processor is typically a high data rate, analog processor it should be placed as close to the front end of the system as possible, before any A/D conversion has taken place. Although one can imagine exceptions, if the signal has already been converted to a digital form and is being adequately handled by the digital electronics, it is very difficult to justify the introduction of an optical carrier. In fact, if a digital system can do the job at all it will generally be the preferred solution because of its fixed error characteristics (i.e., no drift) and its generally convenient size, power, and cost requirements.

If there is a need for the parallel processing of large amounts of stored information, however, the optical processor can rapidly outstrip the digital competition. It's precisely these virtures which have contributed to the success of the single most famous application of optical signal processing yet developed -- the processing of synthetic aperture radar (SAR) data. In spite of our inability to process SAR data in real time until fairly recently,*

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*ERIM results using an experimental thermoplastic electron beam light valve -- private communication from G.D. Currie.

the optical approach has provided the only technique capable of handling the vast amounts of storage and parallel processing required by high resolution SAR continuous strip mapping applications. The optical system's ability to store the data in a two-dimensional transparency format which is directly useable as the input to the optical parallel processing sections (i.e., system of lenses and aperture stops) is key to this success.

The kinds of applications we are seeking for optical signal processing then should be such that they require the optical processor to accept wide bandwidth signals at or near the front end of the system (radar, communication or whatever), temporarily store the data and perform parallel processing operations on this data, perhaps combined with previously stored "filter" data.

3. POTENTIAL APPLICATIONS TO C^3 PROBLEMS

Examining communications, command and control (C^3) from this point of view we can identify a number of potential applications which have requirements for the storage and parallel processing of high data rate information. Radar signal processing is one such area rich in possibilities. However this topic has received a great deal of attention to date* from proponents of optical signal processing and yet, with the exception of the high resolution synthetic aperture radar case, has so far failed to displace the traditional analog methods and digital techniques. For this reason, we have temporarily passed over radar processing and searched further into C^3 for other promising, but even more demanding tasks which could offer the optical implementations better hope of success.

One outstanding candidate has emerged from this search -- spread spectrum processing.† The needs of spread spectrum systems seem ideally matched to the strengths of optical processing. The spread spectrum receiver must accept a wide bandwidth coded signal, correlate it with some kind of stored replica of the code in order to identify at what point in the code sequence the transmitter is currently operating and then use this information to synchronize a decoder to strip the wideband code from the narrower band information signal. Optically one can imagine a processor which accepts a segment of the incoming coded signal, converts this sequence to an appropriate spatial pattern, via a light valve of some kind, and then through an optical

*This is currently under active investigation at Ampex, SAI, Carnegie Mellon, and perhaps other laboratories sponsored by BMDTAC.

†This topic was first brought to our attention by Dr. A. Yang of RADC/ET Hanscom Air Force Base, Bedford, Mass.

parallel processing operation, cross correlates this input segment simultaneously with all parts of the code which has been previously stored in a two dimensional transparency format. Even for long codes, the position of the true correlation peak should be rapidly identifiable from its magnitude and its continuous consistent motion through the code sequence. Having located the "target" (i.e., proper code phase)" through this coarse, wide "field-of-view" search, it could be "handed over" to the high resolution sliding correlation digital search system customarily employed for final code synchronization techniques have much to offer spread sprectrum processing, particularly for long codes. (See Figure 1.)

Looking further, one can even imagine* an optical spread spectrum processor which accepts the coded input in time segments just equal in length to one bit of the low bandwidth information signal; simultaneously cross correlates with stored replicas of the code in its several forms (i.e., corresponding to + and - information bits); and by identifying which version of the code produced the largest correlation peak, correctly identify the information bits without need for code acquisition and synchronization. Information bit synchronization would be required but this should be a much simpler task!

If such a system could be implemented the receiver's tasks would be greatly simplified and spread spectrum technology could perhaps find wider applications. All in all the general consideration augur well for the successful application of optical signal processing techniques to the processing of spread spectrum signals. There seems to be a systems need and an excellent match to optical processing technology as the best features are effectively

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*The details are far from clear. Figure 2 shows one approach.

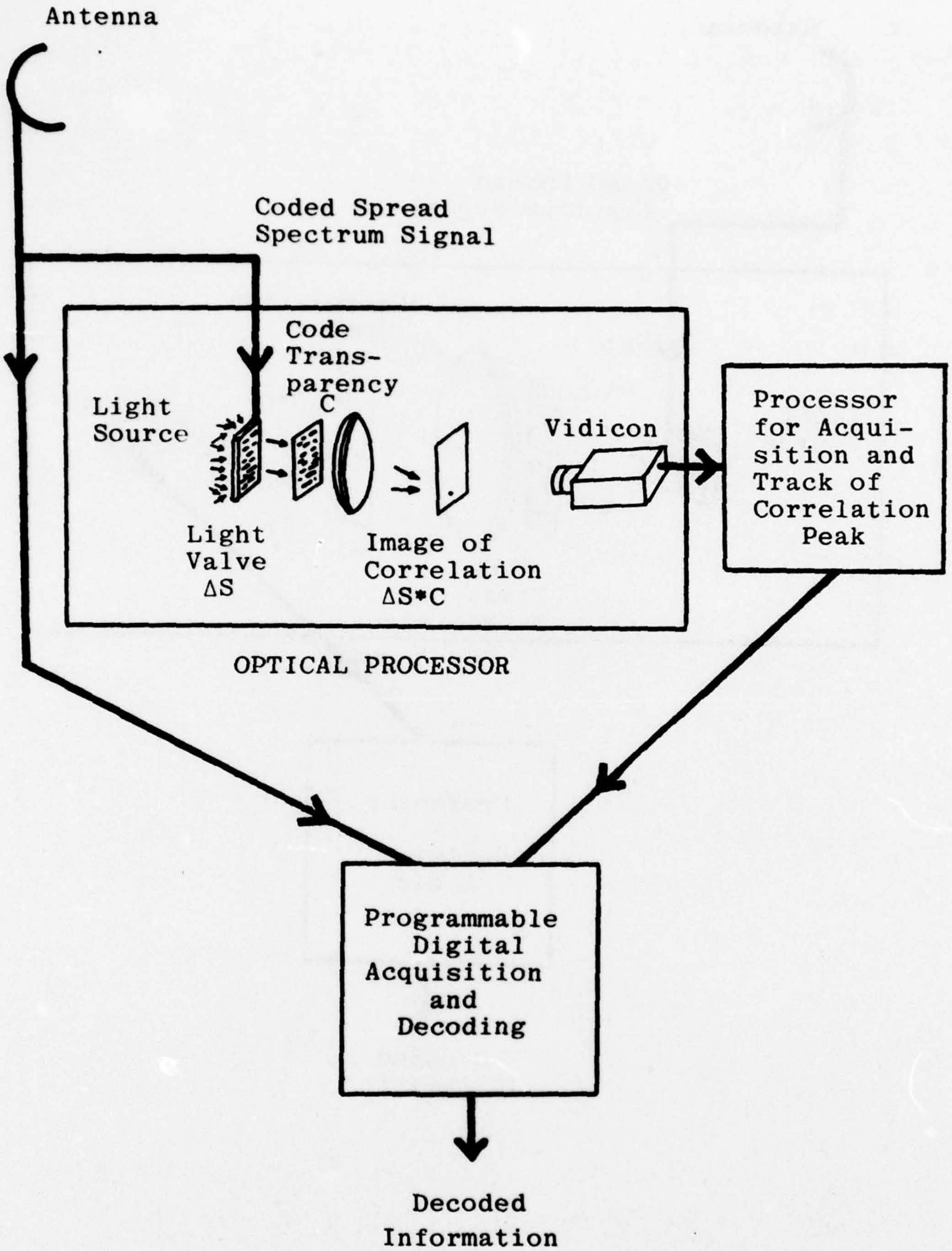


Figure 1: Optical Processor for Rapid Acquisition of Spread Spectrum Codes

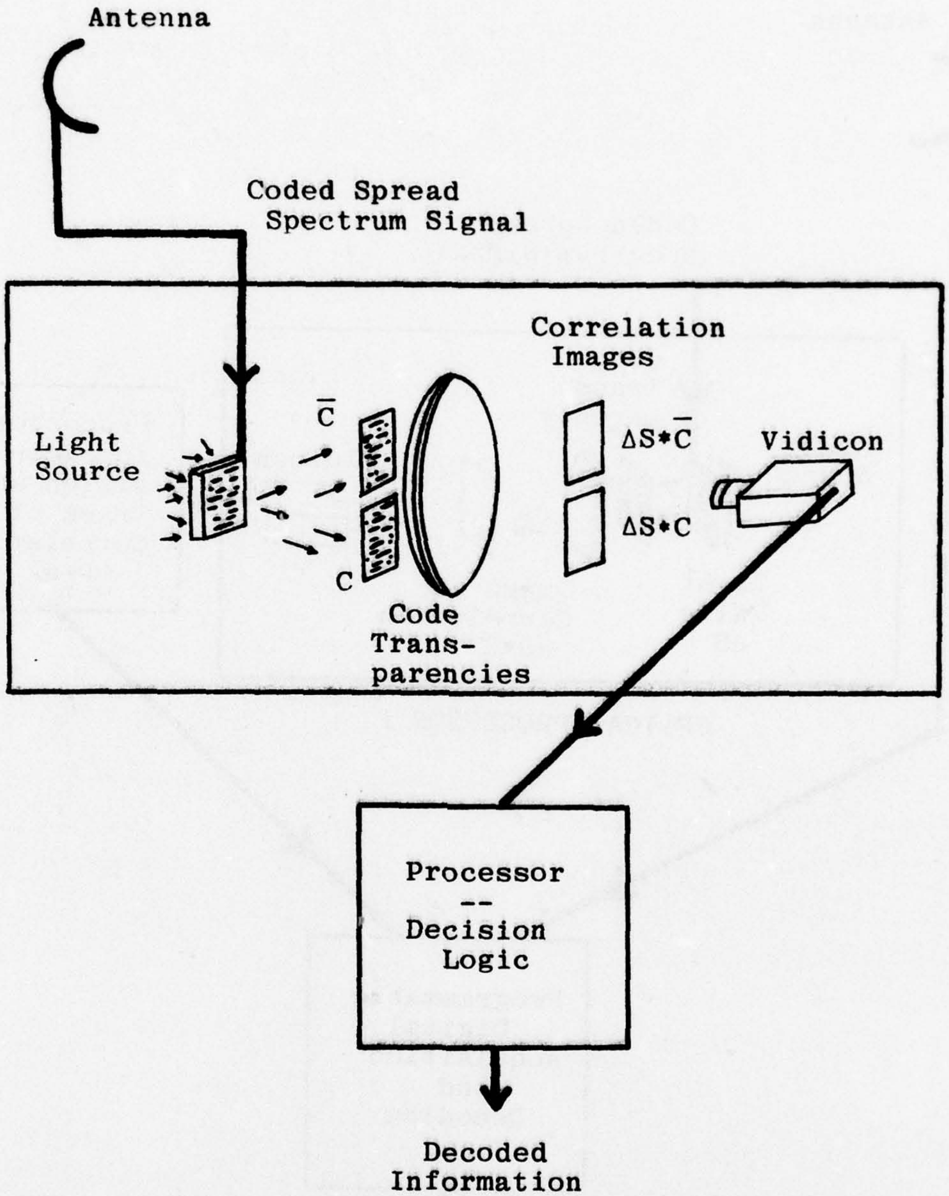


Figure 2: Optical Processor for the Decoding of Spread Spectrum Signals

utilized -- that is, the optical system will provide a high bandwidth front end relying on total code storage and parallel processing!

To this point the discussion has been deliberately general and superficial. We must now begin to address the detailed considerations of how such an optical spread spectrum processor can be best implemented, what are the specific component requirements and what would be the best sequence of experimental and analytical investigations which could be carried out to minimize the time, money, and risks involved in the successful development of this technology.

4. SPREAD SPECTRUM

For the purposes of this initial exploration of the applications of optical signal processing techniques to spread spectrum let us arbitrarily restrict ourselves to bi-phase signals. Other modulation schemes, such as those which depend on time or frequency hopping techniques, can be considered at some later stage.

A typical spread spectrum bi-phase signal[2] is constructed by impressing a high bit rate binary (i.e., ± 1) code C(t) on a similar, but lower bit rate information carrying signal I(t) such that the transmitted signal S(t) has the form

$$S(t) = C(t) \cdot I(t) \cdot e^{i\omega_c t} \qquad (1)$$

where the exponential term represents a narrow band carrier and the code and information function C(t) and I(t) take on only the binary values of ± 1. The bit rate of the code can be as much as 10^3 times higher than that of the information and the specific code sequences chosen are selected partially on the basis of their noise-like spectral characteristics. Thus if not decoded, a spread spectrum signal will look much like a noise signal with a bandwidth which is approximately two times the code bit rate with the information signal effectively buried in the noise. Figure 3 illustrates such a bi-phase code.

In order to decode a bi-phase spread signal of the form indicated in eq. 1, the receiver must first have a code generator capable of generating the correct code at the correct bit rate. Then he must identify what portion of the code is correctly being transmitted and synchronize his code generator to it; that is, he must "acquire" the

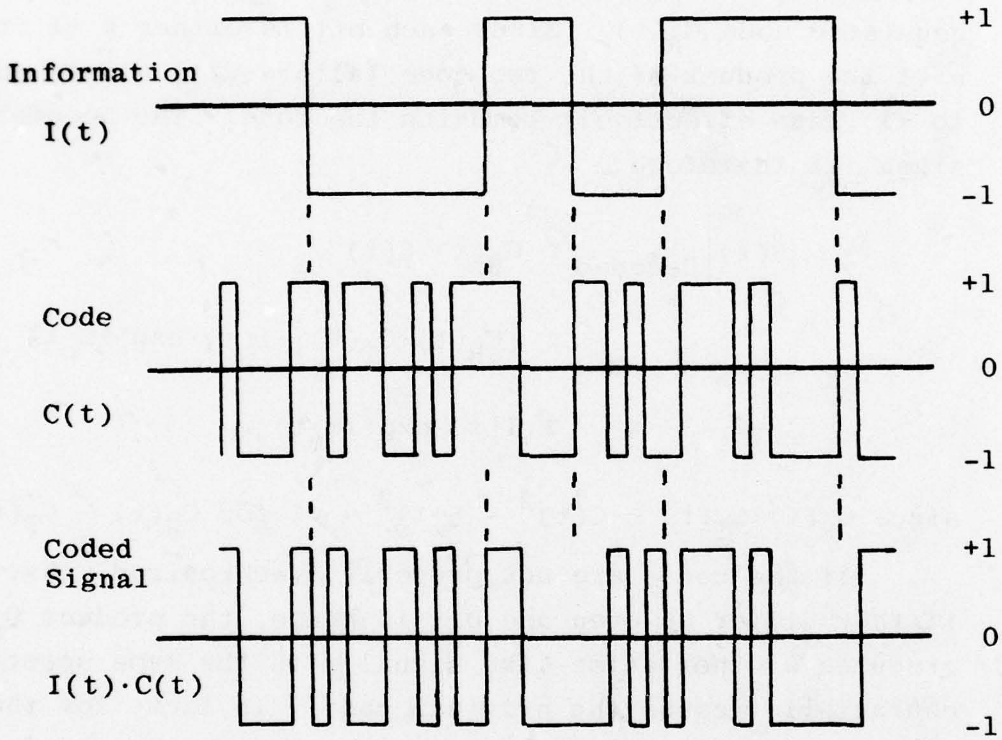


Figure 3: Typical Bi-Phase Code Used for Spread Spectrum Transmission

code. In practice, this can be an extremely difficult task as codes with periods as long as minutes, hours or even days can be readily generated. With the code generator of both the transmitter and receiver properly synchronized to the same bit, the decoding is accomplished by simply multiplying the incoming signal S(t) by the receiver-generated code $C_R(t)$. Since each bit is either a +1 or a -1 the product of the two code factors will always square to +1, thus effectively removing the code. The decoded signal is therefore

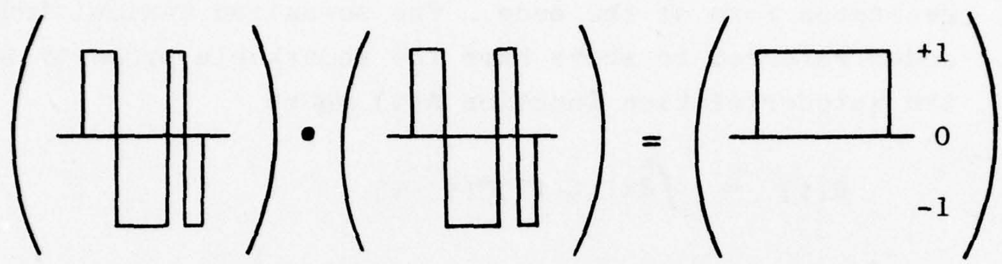
$$\begin{aligned} \left|S(t)\right|_{\text{Decoded}} &\equiv C_R(t)\cdot S(t) \\ &\equiv \left|C_R(t)\cdot C_T(t)\right|\cdot I(t)\cdot \exp(i\omega_c t) \\ &\equiv I(t)\cdot \exp(i\omega_c t) \end{aligned} \tag{2}$$

since $C_R(t)\cdot C_T(t) \equiv C(t)^2 = (\pm 1)^2 = +1$ for $C_R(t) \equiv C_T(t)$.

If the codes are not properly synchronized, that is, if they differ by even one bit in phase, the product $C_R\cdot C_T$ produces another noise-like signal with the same spectral characteristics as the original code. In fact, for the commonly used maximal-length shift-register generated codes[2] the product of two phase-shifted versions of the same code is simply another version of the same code with some other phase; that is

$$C(t-t_1)\cdot C(t-t_2) \equiv \begin{cases} C(t-t_3) & t_1 \neq t_2 \\ +1 & t_1 = t_2 \end{cases} \tag{3}$$

Obviously code acquisition and precise synchronization is an absolute prerequisite for successful decoding!



C(t) • C(t) = +1

Figure 4: Decoding by bit-by-bit multiplication of two perfectly synchronized versions of the same code

Mathematically, the proper phase of the code can be determined by considering the cross section between the incoming code and the various possible phase shifted versions of the same code obtained from a stored or locally-generated form of the code. The so-called maximal length codes referred to above have the remarkable property that the autocorrelation function A(t) where

$$A(t) = \int dt' \, C(t')C(t'-t) \tag{4}$$

has single peak corresponding to zero phase shift (i.e., t = 0) and is a constant for all phase shift differences greater than $\pm$ one bit (i.e. $|t| > 1$). Such an autocorrelation is illustrated in Figure 5a. The ratio of peak to side lobe level is precisely equal to the total number of bits N in the code. This property of maximal length codes is strictly true only when full length code sequences are used, that is, the integration in eq. 4 must extend over the full period of the code and the code sequences are assumed to be repeated continuously, as if they were wrapped around a cylinder.

Unfortunately, in practice the incoming code is generated in time and unless the receiver can wait through one full code sequence, a complete version of the incoming code will never be available. Under these circumstances the next best bet is to select a reasonable length sample of code and cross correlate this with the stored code -- that is, conceptually slipping it along the stored code and multiplying and summing to compute the cross correlation. Obviously when the proper segment of the stored code is found the product of the two codes will be uniformly equal to +1 and a peak correlation will occur with the summation just equal to the total time length of the segment chosen. For other positions some bit disagreement will occur giving rise to negative contributions to the sum, which inevitably

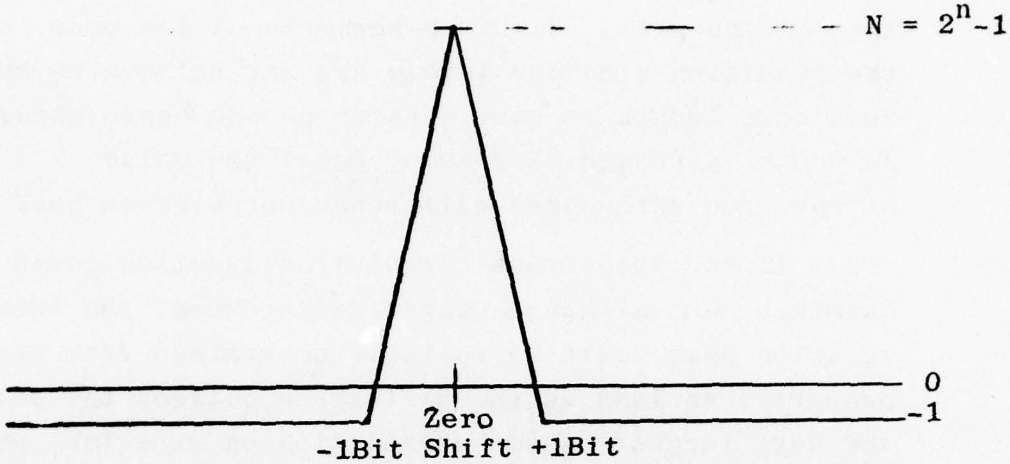


Figure 5a

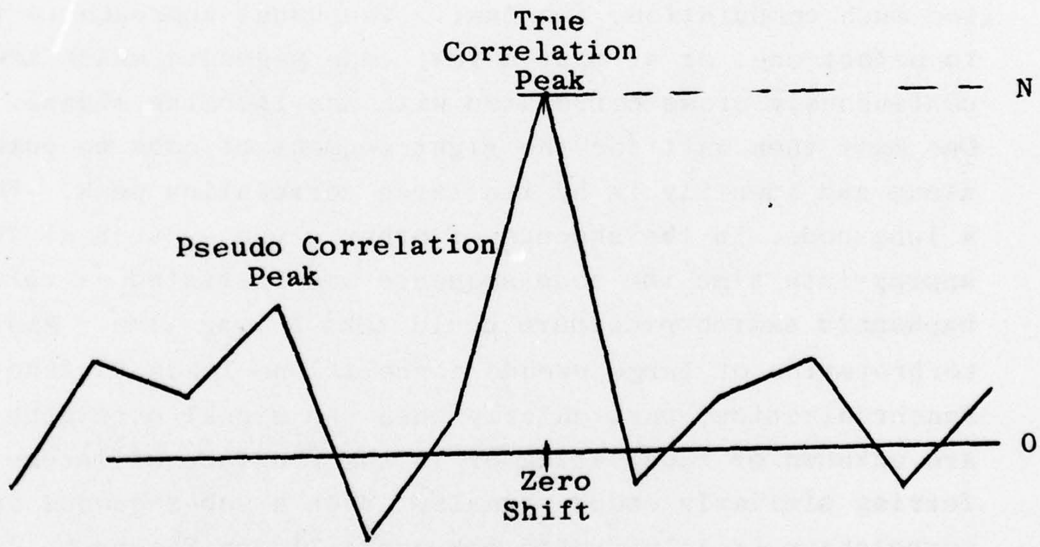


Figure 5b

Figure 5

a) **Autocorrelation of total maxima length shift register code.**

b) **Cross correlation of code sub-segment with full length code.**

reduce the value of the cross correlation function below that of the peak. With sub-segments of the code, however, the resulting sidelobe levels are not uniform as when the full code length is used. Large pseudo correlation peaks do occur, although they never equal the value of the true zero-phase difference correlation peak.

If the full cross correlation function could be examined for all phase shift differences, the true correlation peak could be reliably determined from its maximal property, as long as the difference between the peak and the next largest pseudo-correlation on side lobe peak sufficiently exceeds the signal to noise ratio. With the digital processing techniques currently used to implement spread spectrum decoders, this is never a valid alternative. For practical code lengths and bit rates, it simply requires too much computation, too fast. The usual approach is then to select one, or at most a few, code segments which are continuously cross correlated with the incoming signal. One must then wait for the right segment of code to come along and identify it by its large correlation peak. For a long code, in the absence of other clues -- such as the appropriate time the code sequence was initiated -- this haphazard search procedure could take a long time. Misinterpretation of large pseudo correlations leads to fake synchronization, particularly when the signal strengths are unknown or fluctuating or in the presence of interferring similarly coded signals. Such a sub-sequence cross correlation is illustrated schematically in Figure 5b, and may be contrasted with the true autocorrelation depicted in Figure 5a.

5. OPTICAL CODE ACQUISITION

If we now consider the possibility of an optical implementation of the cross correlation code acquisition search it appears that because of the "speed-of-light," parallel processing capabilities of optical signal processing, a phase search of the total code sequence in real time may well be practical. It is possible for an optical correlator to select a segment of the incoming signal, convert it into a suitable one or two dimensional image and cross correlate it simultaneously with all sections of the complete code which has been stored as an appropriate one or two dimensional transparency. The resulting cross correlation function will generally be available in the form of a spatial image which can then be examined to identify the position, and hence phase, of maximum correlation. Once the input signal segment is available, the actual computation of the correlation function is carried out in the time it takes for light to propagate through the optical system -- typically only a few nanoseconds at most. The search for the peak will then take more time but can reasonably be carried out in a millisecond or less with more or less conventional image scanning techniques. Of course, since the code continues to change with time, the peak of the correlation will continue to move systematically through the code sequence giving rise to a correlation spot which moves at a constant velocity in the correlation "image." This consistent trajectory will also be useful in distinguishing the time correlation peak from the pseudo correlation fluctuation which should show no such uniform motion, but rather "flash" on and off. Several scans of the correlation image will thus be necessary before the peak can be reliably detected. With the correlation peak position and "velocity" estimated, it should be a simple matter to handover to the standard digital (narrow field of view) acquisition sensor which can be quickly programmed with a code segment chosen to be just ahead of the present phase of the received code. From this point on conventional digital practice will be adequate for precise code synchronization, track maintenance (phase locked loops or whatever), and decoding.

As has been deliberately suggested by the terminology used in the above discussion, the optical correlation step transforms the time phase synchronization problem into a standard spatial search and acquisition scenario. The code acquisition is thus no longer determined by the bit rate of the code but by the time required to successfully conduct the spatial search.

5.1 Effects of Doppler

So far, it has been tacitly assumed that an optical correlation technique may be applied to the base band code signal. This implies that the RF carrier (which is automatically "suppressed" by the balanced modulation imposed by the code) is somehow available at the receiver, and that the spread spectrum signal is accordingly heterodyned to base band without phase corruption.

Were it not for Doppler, or time varying multipath effects on the communication channel (and in certain circumstances peculiar effects on clocks predicted by Einstein)*[4], it would be feasible to supply the suppressed carrier with an onboard frequency standard such as a Maser. In view of these problems, however, a more practical approach is to

*Brought to our attention by Mr. Clare C. Leiby Jr. of RADC/ET, Hanscom AFB, Bedford, Massachusetts.

extract the "suppressed" carrier from the received spread spectrum signal itself. Figure 6 shows this may be facilitated by simply squaring the biphase signal, $S(t)\cos(\omega_c t)$, to generate $\frac{1}{2}(1 + \cos(2\omega_c t))$, since $(S(t))^2 = 1$. This signal at twice the carrier frequency will be corrupted by noise, and it must be tracked (Figure 7) with a phase-locked loop and then halved to create the desired carrier frequency. Alternatively, a Costas loop (Figure 8) may be used instead of the squaring loop. The Costas loop appears more complicated than the squaring loop, but detailed analysis shows they are equivalent.[5]

An appreciation of this fact may be gained by observing that both the squaring loop and the Costas loop employ nonlinear operations (squaring and mixing) and that both rely upon phase-locked loops. Digging a little deeper into the operation of the Costas loop, suppose that the VCO (Voltage Controlled Oscillator; an oscillator whose frequency, ω, is controlled by an input voltage, v: $\dot{\omega} = -v$) of the phase locked loop is momentarily oscillating at $\cos(\omega_c+\varepsilon)t$, while the input spread spectrum signal is $S(t)\cos(\omega_c t)$. The mixer in the top branch of the circuit then produces a signal of $S(t)\cos(\omega_c t)\cos((\omega_c+\varepsilon)t)$; the mixer in the lower branch, a signal of $S(t)\cos(\omega_c t)\sin((\omega_c+\varepsilon)t)$. These signals are then mixed again to produce a signal of $(S(t))^2 \cos^2(\omega_c t)\cos((\omega_c+\varepsilon)t)\sin((\omega_c+\varepsilon)t)$. (At this point, notice that a factor $\cos^2(\omega_c t)$ appears, just as in the squaring loop!) A little trigonometry shows that this product of signals contains a low frequency component of $v = \frac{1}{8}(S(t))^2 \sin(\varepsilon t)$, which is isolated by a lowpass filtering operation. In time, the VCO changes its frequency to reduce v, and in the process $\varepsilon \to 0$, so the VCO locks onto the carrier ω_c. An analysis of the phase-locked loop in the presence of noise has been carried out by Viterbi.[6]

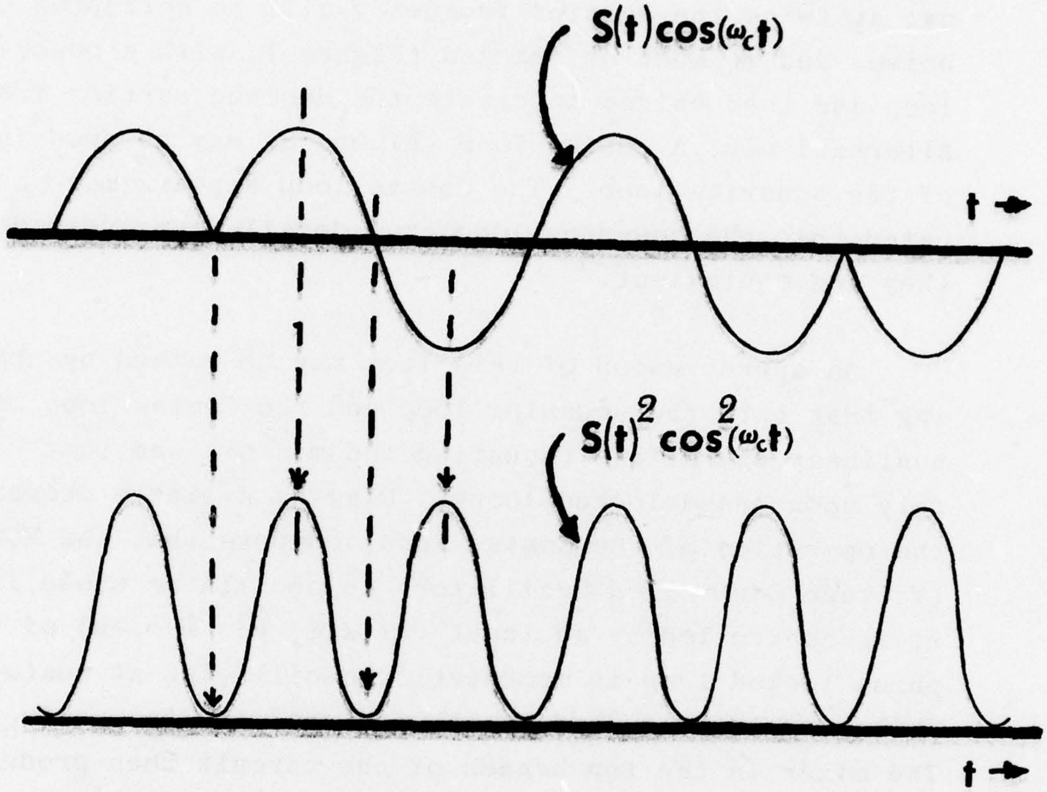


Figure 6. Squaring to extract ω_c

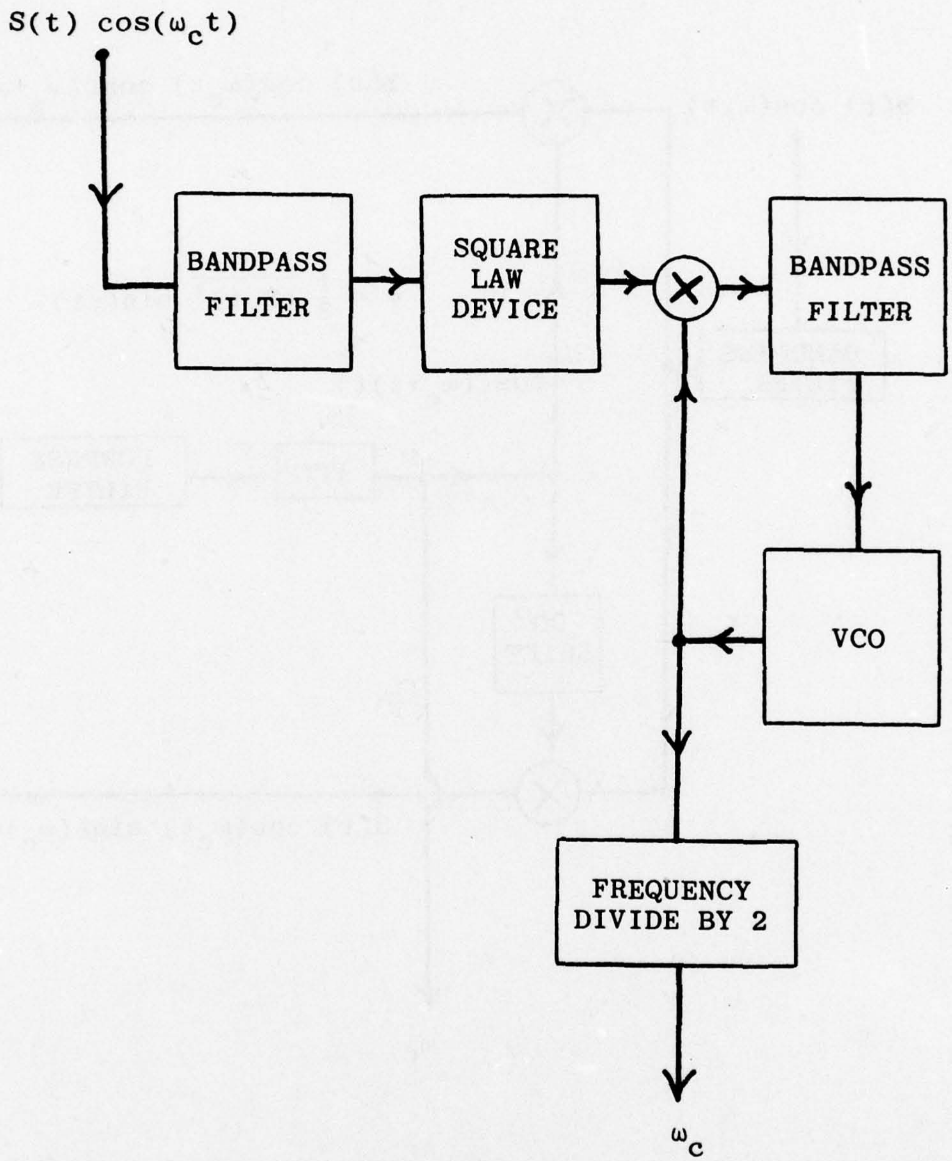


Figure 7. Squaring Loop

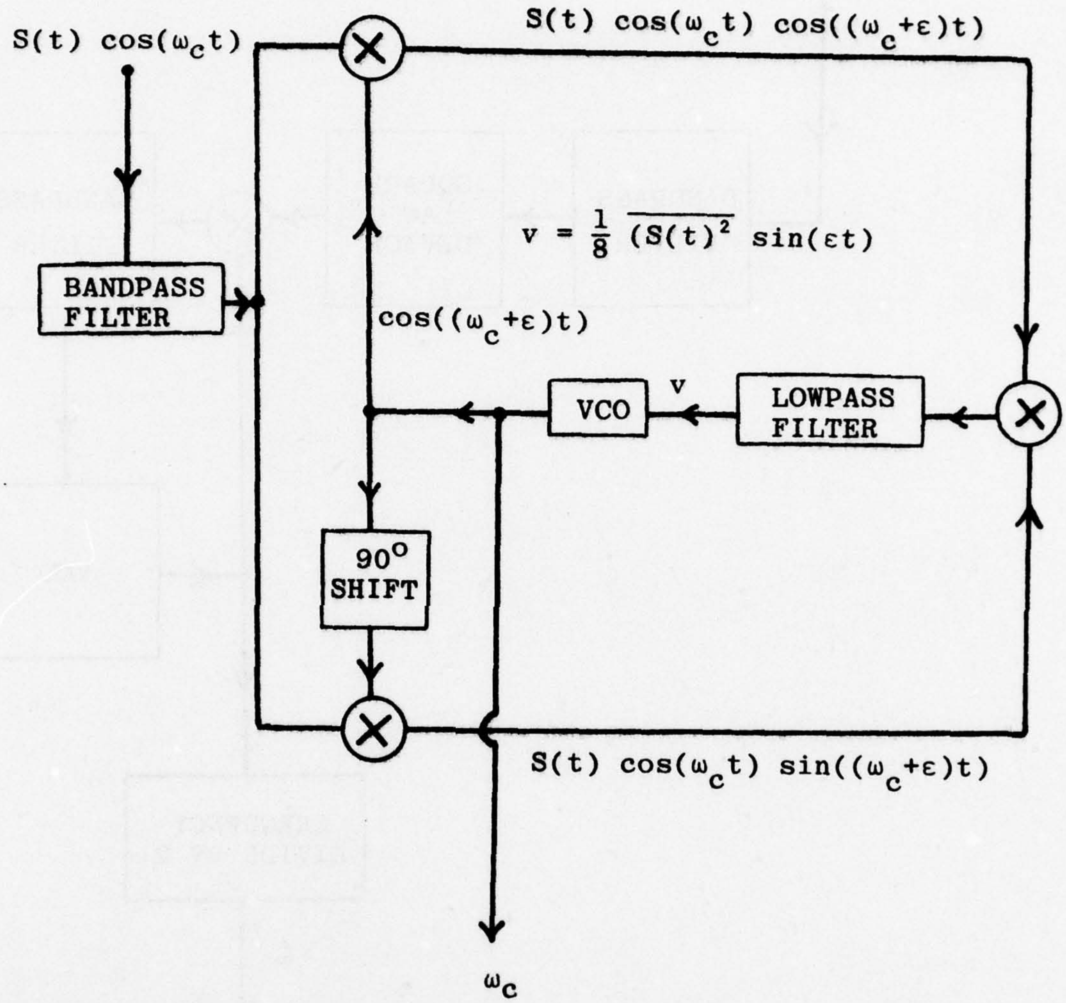


Figure 8. Costas Loop

5.2 Hand Over of Synchronization

The requisite shift register tapping network[2] having been previously specified, the receiver code generator requires but two additional pieces of information:

(1) the instantaneous code rate, and
(2) the instantaneous code phase.

We have observed (Section 5.1) that a squaring loop or Costas loop may be used to acquire the carrier frequency; the code rate may be obtained by frequency division of the carrier, because the transmitted code is generated in synchronism with the carrier.

The code phase must somehow be derived from the position of the correlation peak in the output image of the correlator (Figure 1). Operationally, the code phase corresponds to the binary word residing in the shift register.[2] If the proper binary word could be determined from the position of the correlation peak, the word could be loaded into the shift register, and synchronization would be accomplished.

One way to do this is to interrogate a transparency replica of the code with a deflected light beam which tracks the position of the peak in the correlator output image, as in Figure 9. Since the handover operation will involve some delays, it may prove necessary to "look ahead" in the code sequence during this interrogation step; this may be accomplished by simply offsetting the position of the light beam. In any event, the major synchronization job is complete, and tracking of the code to maintain synchronization may be performed with a delay-lock loop.[7]

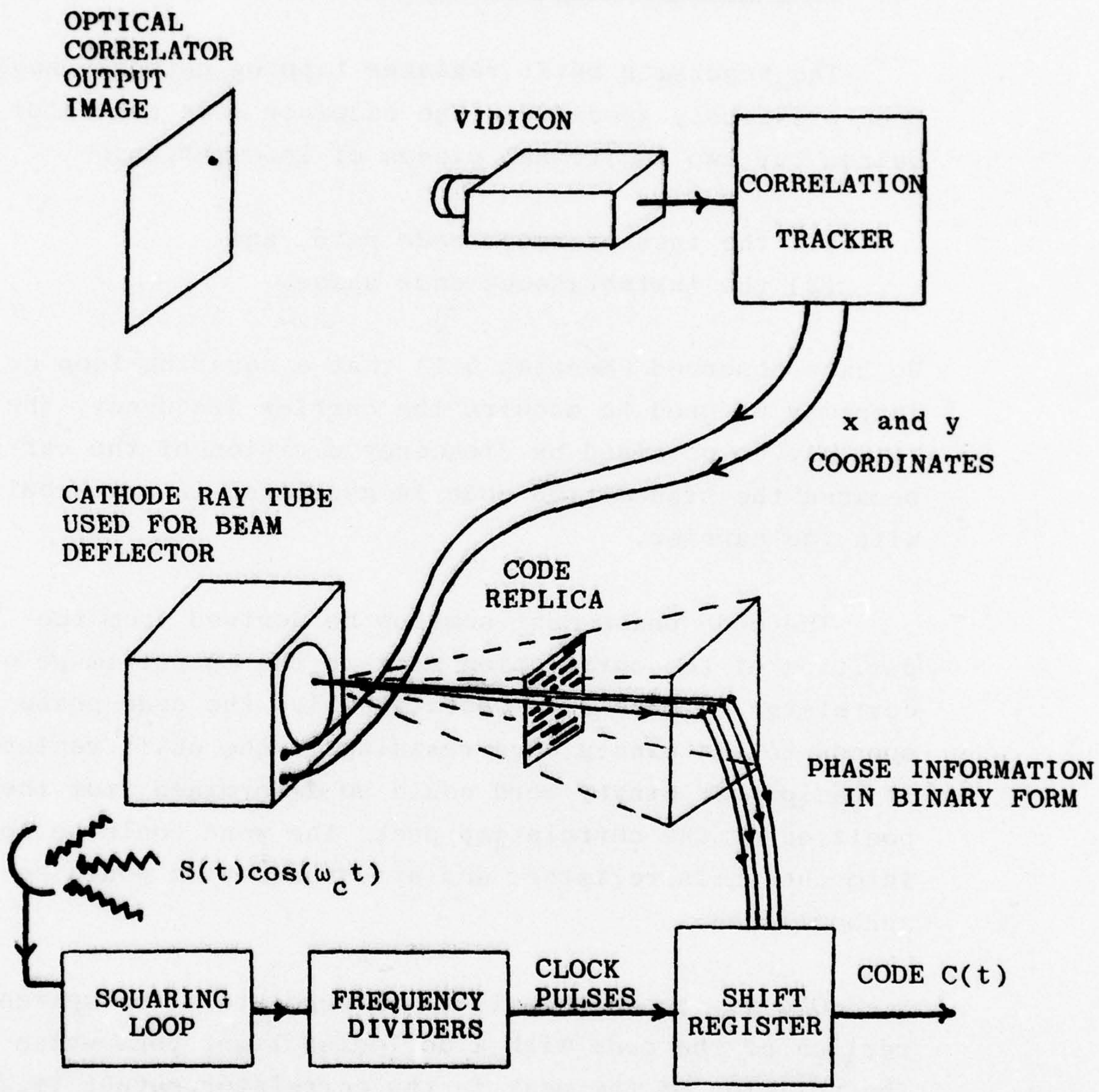


Figure 9. Handover of synchronization

C. POSSIBLE OPTICAL CONFIGURATIONS

The mathematical operation to be carried out by the optical processor for this spread spectrum application is cross correlation. That is, given a segment $\Delta S(x)$ of the incoming code in a one dimensional spatial format, and a stored version of the code $C(x)$ we must compute the function $A_{\Delta S}(x)$

$$A_{\Delta S}(x) = \int dx' \; \Delta S(x') \; C(x'-x) \equiv (\Delta S * C) \qquad (5)$$

for all values of x over the length of the code $L = N\Delta x$, where N is the total number of bits in the code and Δx is the spatial interval corresponding to the representation of one bit. For long codes, a one dimensional representation will not be practical so the code will have to be compressed into a two dimensional raster. Proper regard must be paid to the overlap at the ends of each line so that the breaks in the code continuity do not produce "blind spots" -- that is, sections of code which are physically split into two parts, one on each of two adjacent raster lines such that a good correlation with the same unsplit segment is not possible.

6.1 Geometric Optics Incoherent Processor

There are several general optical signal processing techniques available which are capable of implementing the cross correlation process defined by eq. 5. The simplest in concept, although definitely not the most efficient in practice, involves a direct, brute force application of incoherent optics. Consider the optical configuration illustrated in figure 10. The code has been recorded as a series of holes in an otherwise opaque filter plane --

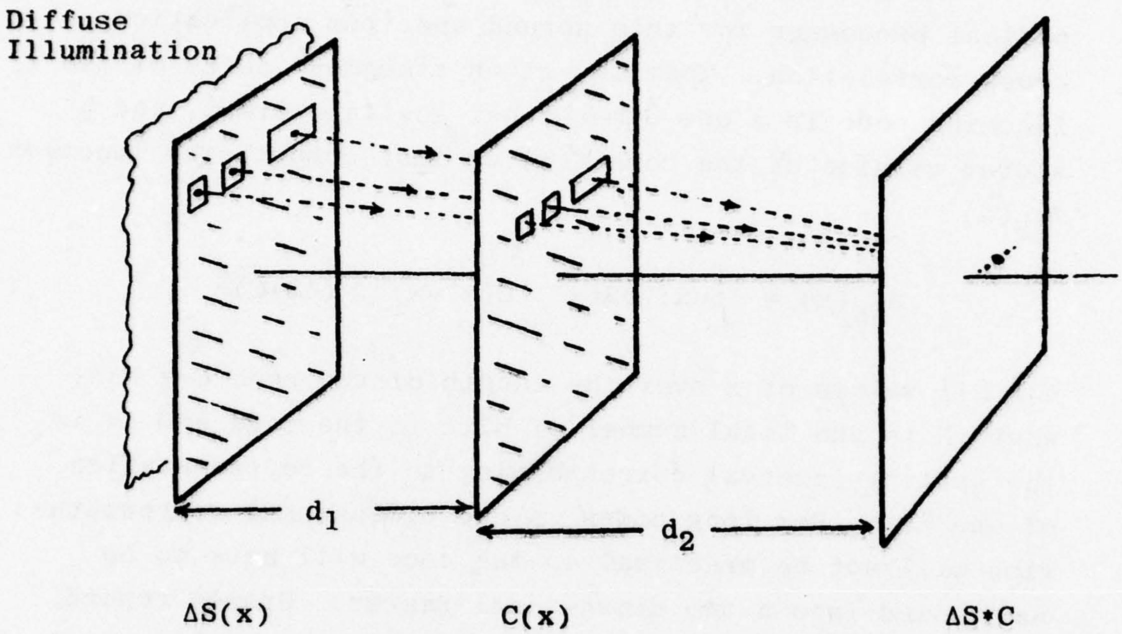


Figure 10: "Brute Force" Geometric Incoherent Optical Processor for calculation of the cross correlation function $\Delta S*C$.

say a hole for each +1 bit, and no hole for each -1 bit. The incoming coded segment is written as a similar linear array of transparent and opaque areas by means of some kind of light valve which is compatible with the received signal properties. For example, this could be a GE light valve, the ERIM thermoplastic unit or any other electron beam addressed light valve or even a snapshot acoustic device using a Bragg scatter bulk delay line and a flashed light source.[1] For purposes of study we can give up the real time aspect and simply make the input a photographic transparency or aperture mask.

If an incoherent light source is placed such that it illuminates the "image" or correlation plane as indicated in the figure, it can be shown that in the limit of geometric optics (that is, neglecting diffraction effects) the image plane illumination can be described as a "convolution" of the two transparencies.

$$I(x)_{\substack{\text{Image}\\\text{Plane}}} \sim \int dx' \; T_1(x') \; T_2\left(\frac{d_1 x + d_2 x'}{d_1 + d_2}\right) \qquad (6)$$

where T_1 and T_2 represent the two mask transparencies and d_1 is the distance between the mask and d_2 the distance from the second mask to the image plane as illustrated in figure 11.

Physically it is clear that if the two aperture masks are scaled properly by the ratio of the distances from the image plane, there will be a point of maximum light where the illuminated bits of the input code sub-sequence can be "seen" through the aperture holes of the code mask which correspond to this same code sub-sequence. For any other point in the image plane some of the illuminated bits of the input will be blocked by opaque parts of the code mask and the illumination level will be reduced.

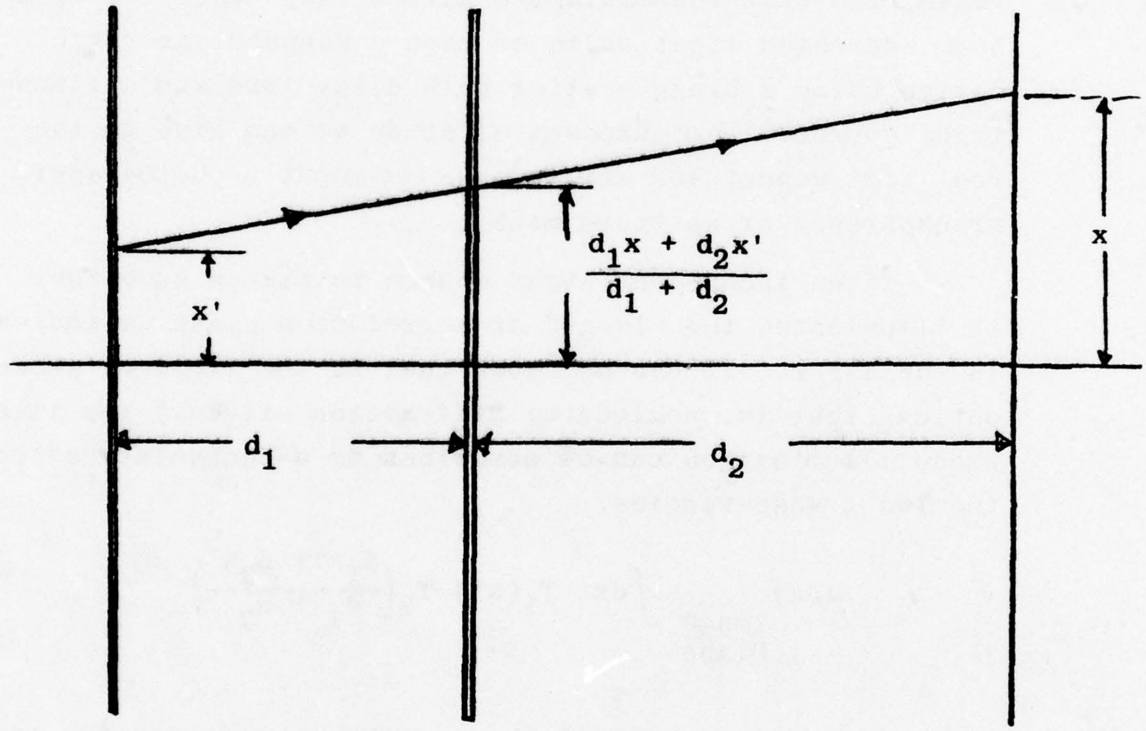


Figure 11: Geometry of geometric optics incoherent processor.

For a small enough code, large mask elements can be considered and the neglect of diffraction can be a reasonable assumption. Under these conditions, this simple incoherent optical processor will, in fact, generate an illumination plane distribution which represents the complete cross correlation functions simultaneously generated for all possible displacements.

For the larger codes of practical interest, smaller mask dimensions are inevitable if the full code is to be compressed on to a reasonable sized two-dimensional format. Using a nominal bit dimension of 1μ we see that at least N square microns or N x 10^{-8} square centimeters are required for an N bit code. The minimum mask areas required by various codes are presented in table 1 for a number of maximal length codes.

Shift Register Length, n	Code Sequence Length $N=2^n-1$	Sequence Period at 100 Mbps rate	Estimated Optical Mask Area for Total Code
7	127	1.3 μ sec	$1.3\times10^{-6}cm^2$
8	255	2.6 μ sec	$2.6\times10^{-6}cm^2$
9	511	5.1 μ sec	$5.1\times10^{-6}cm^2$
10	1,023	10.2 μ sec	$1.0\times10^{-5}cm^2$
11	2,047	20.5 μ sec	$2.0\times10^{-5}cm^2$
12	4,095	41 μ sec	$4.1\times10^{-5}cm^2$
13	8,191	82 μ sec	$8.2\times10^{-5}cm^2$
17	131,071	1.3 m sec	$1.3\times10^{-3}cm^2$
19	524,287	5.2 m sec	$5.2\times10^{-3}cm^2$
23	8,388,607	84 m sec	$8.4\times10^{-2}cm^2$
27	134,217,727	0.13 sec	$1.3cm^2$
31	2,147,403,647	0.36 min	$21.5cm^2$
43	879,609,302,207	1.02 days	0.88 $(\text{meters})^2$

Table 1

Estimated Mask Area Required by Maximal Length Codes

Of course with dimensions on the order of a micron, severe diffraction effects are inevitable and the incoherent correlator suggested above will not work for large codes. The diffraction will wash out or obscure the correlation structure we are interested in.

6.1.1 Diffraction Limits

The effect of diffraction on the simple incoherent processor described above can be roughly estimated in terms of Fresnel near-field diffraction concepts. In reference 8 the limit of geometrical optics is discussed where it is shown that for a slit of width ΔL, placed a distance d from the source and distance d_2 from the shadow or image plane (figure 11) diffraction effects can be neglected when

$$\Delta L \sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2}\right)} \gg 1 \tag{7}$$

If we take this as determining the lower size limit on bit sizes in the code filter plane, we can estimate the size of the code we might hope to process with the simple processor. The number of bits of area ΔL^2 which can be stored on an L by L square filter is given by

$$N \simeq \frac{L^2}{\Delta L^2} \tag{8}$$

which by eq. 7 must be limited by

$$N \leq 2 \frac{L^2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2}\right) \tag{9}$$

For visible light ($\bar{\lambda} \simeq 5 \times 10^{-5}$ cm) this becomes

$$N \leq 4 \times 10^4 L^2 \left(\frac{1}{d_1} + \frac{1}{d_2}\right) \tag{10}$$

For example, if we assume $d_1 = d_2 = L = 10$ cm we find that

$$N \leq 2 \times 10^5 \text{ bits} \tag{11}$$

and each bit would be approximately $\sqrt{\lambda d} \simeq 1/5$ mm on a side. Apparently, it may be practical to apply this very simple incoherent correlation to reasonable large codes -- 2×10^5 bits exceeds the size of a 17 shift register maximal length code.

6.2 Alternate Approaches to Incoherent Processing

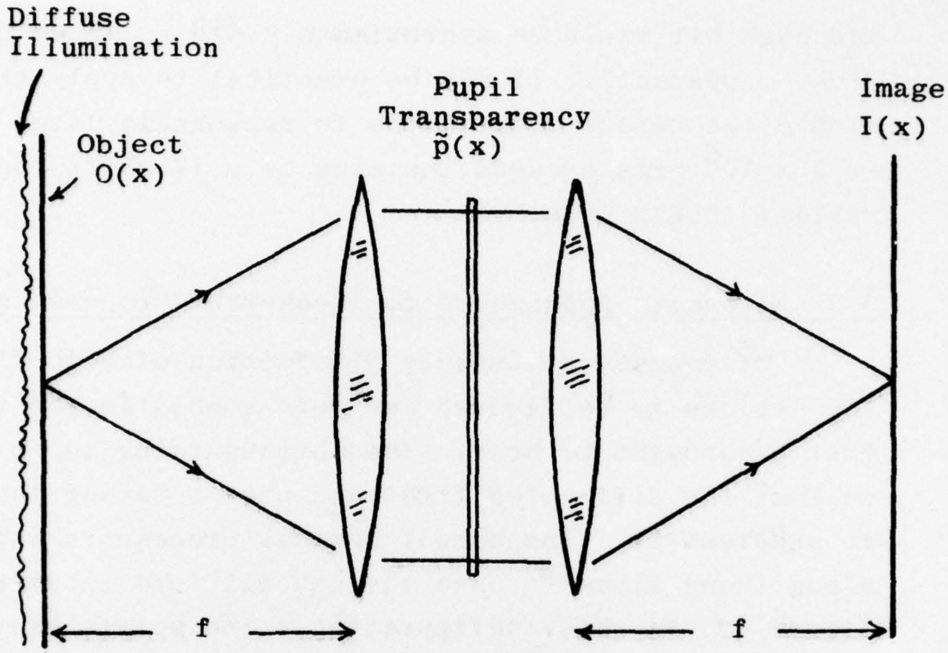
Of course, ultimately diffraction effects will become too serious to be ignored and more sophisticated techniques must be brought to bear. The obvious thing to do is to collect the diffracted light and use it rather than trying to suppress it. Incoherent optical processors which operate along these lines(3) have the general form illustrated in figure 12. In this configuration, the split lens pair acts to image the object plane into the image plane, such that

$$I(x) = O(x) \circ F(x) \quad \text{(convolution)} \tag{12}$$

where the system impulse response or intensity point spread function (PSF) $F(x)$ is equal to the square of the magnitude of the Fourier transform of the pupil function $\tilde{p}(u)$. Each object point considered by itself produces a uniform coherent* illumination of the filter transparency or pupil function $\tilde{p}(u)$ and the second lens then generates its fourier transform $p(x)$ in the image plane. The intensity point spread function $F(x)$ is thus

$$F(x) = |p(x)|^2 \tag{13}$$

*that is, spatially coherent



$$I(x) = O(x) \circ |p(x)|^2$$

where

$p(x) \equiv$ Fourier Transform of $\tilde{p}(u)$

Figure 12: Incoherent Optical Processor which uses diffraction

If we now integrate over the incoherent distribution of sources in the object plane, eq. 12 immediately follows. The Fourier transform of the point spread function $\tilde{F}(u)$ is proportional to the standard optical transfer function (OTF), and in virtue of eq. 13 and the well known properties of convolution products and Fourier transforms is given by the autocorrelation of the pupil function $\tilde{p}(u)$; that is

$$\begin{aligned} \tilde{F}(u) &= \tilde{p}(u) * \tilde{p}(u) \\ &= \int_{-\infty}^{\infty} du' \, \tilde{p}(u')\tilde{p}(u'+u) \end{aligned} \tag{14}$$

To apply this form of incoherent optical correlator to the acquisition of a spread spectrum code we need only identify $O(x)$ in eq. 12 as the input segment $\Delta S(x)$ and $F(x)$ as the stored representation of the full code $C(x)$. So far so good, for coincidently the binary codes we wish to use are naturally real and positive as required by eq. 13! However, the filter transparency which is physically inserted in the system must represent not the code but, in some sense, the Fourier transform of its square root.

Here we come face to face with one of the most difficult issues associated with the successful implemention of this form of incoherent optical processing, that of selecting a pupil function $\tilde{p}(u)$, which when Fourier transformed and magnitude squared will produce the desired point spread function $F(x)$. This is not a well defined mathematical problem with a unique answer, for one can immediately construct an infinity of possible pupil functions which will result in the same point spread function $F(x)$. For example, if we consider the product of $\sqrt{F(x)}$ and <u>any</u> arbitrary phase factor $\exp\,[i\phi(x)]$ we have a candidate $p(x)$; i. e.,

$$p(x) \equiv \sqrt{F(x)} \cdot \exp|i\phi(x)| \tag{15}$$

which when Fourier transformed leads to a pupil function $\tilde{p}(u)$ which satisfies our requirements. Since there is an infinity of arbitrary phase factors $\phi(x)$ we can conjure up, there must be an infinity of pupil functions $\tilde{p}(u)$ which solve the problem.

If this was all there was to the problem we would have no difficulty at all; since ϕ can be arbitrarily chosen let us choose it equal to zero and compute $\tilde{p}(u)$ as the transform of $|\sqrt{F(x)}|$. In our case, where F(x) represents a binary code C(x) where C can be only +1 or 0, a convenient simplification occurs; that is

$$C(x) \equiv C(x)^2 = |\sqrt{C(x)}| \equiv (+1,0) \tag{16}$$

and hence it would appear that a suitable $\tilde{p}(u)$ could be obtained by simply transforming the code such that

$$p(x) \equiv C(x) \rightarrow \tilde{p}(u) \tag{17}$$

If we attempt this we see immediately where the real obstacles lie. A function with square corners such as C(x) has a Fourier transform which extends to infinity -- but the lenses and filter transparency illustrated in figure 12 are finite in size. If the $\tilde{p}(u)$ generated by the recipe above is inserted to a real optical system, the point response F(x) which actually appears in the output plane will not be C(x) but only an approximation to it; in a sense, a low pass filtered version. In other words, because of the lenses finite apertures, only a diffraction-limited image of C(x) is possible.

The mathematical problem we must resolve to implement this form of incoherent optical processor can now be more properly defined as follows:

- Given a desired point spread function $F(x)$, find the band-limited pupil function $\tilde{p}(u)$ which produces the "best" approximation to $F(x)$ when Fourier transformed through the finite lens aperture available.

A natural definition for "best" is to choose $\tilde{p}(u)$ such that the mean square error E between $|p(x)|^2$ and described $F(x)$ is minimized; that is

$$E = \int_{\substack{\text{Output}\\ \text{plane}}} dx \left[|p(x)|^2 - F(x) \right]^2 \tag{18}$$

Of course, this is an arbitrary choice and other definitions of "best" may be more suitable for particular applications.

Generally, the required pupil function $\tilde{p}(u)$ will be complex, that is, it will have both an amplitude and a phase. While physically implementing such a "transparency" can be difficult, it is certainly possible by a variety of techniques.[3] However, since some forms, e.g., phase only or amplitude-only, etc., are often simpler to produce by whatever particular process is being utilized, it is interesting to consider additional restrictions on the pupil function $\tilde{p}(u)$. For example, since a real, positive transparency is particularly easy to fabricate we might ask: What real positive aperture-limited pupil function $\tilde{p}(u)$ will result in the "best" approximation $|p(x)|^2$ to the desired point response function $F(x)$? At the moment, little is known concerning the answers to this type of question. However, there are formal techniques of "optimal estimation" which have been developed to resolve such "best" approximations, constrained problems in systematic ways. In the future, this issue will hopefully get the complete analysis it deserves.

Returning now to the particular problem at hand -- spread spectrum -- we note that the point spread function F(x) which we hope to generate in the output plane can at best be some diffraction-limited image of the code C(x). However diffraction plays an entirely different role here than it did in the case of the "geometric optics" processor first described. Considering Figure 13 it can be shown that if ΔL is the smallest resolvable bit which can be recorded on the filter plane, the field of view L_{max} in the image plane is given approximately by

$$L_{max} \simeq 2\lambda f/\Delta L \tag{19}$$

and by the usual diffraction-limited expressions for the resolution of a uniformly illuminated aperture, the smallest resolvable bit Δx which can be produced in the image plane is approximately

$$\Delta x \simeq 2\lambda f/L \tag{20}$$

Thus the total number N of bits we can produce in the image plane is

$$N \simeq \frac{\text{Area of FOV}}{\text{Area of resolvable bit}} \simeq \frac{L_{max}{}^2}{\Delta x^2} \simeq \frac{L^2}{\Delta L^2} \tag{21}$$

But $L^2/\Delta L^2$ is just the total number of bits we could record in direct form on the filter; precisely the number which have been presented in the table. Thus the more sophisticated form of incoherent optical processing successfully overcomes the diffraction-limitation of the geometric optical correlator as anticipated.

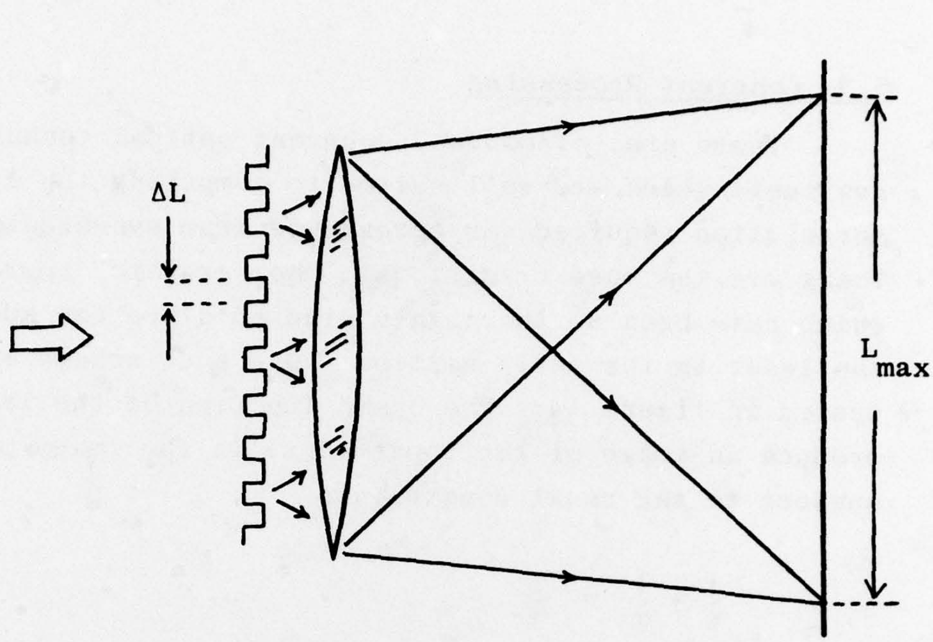


Figure 13a

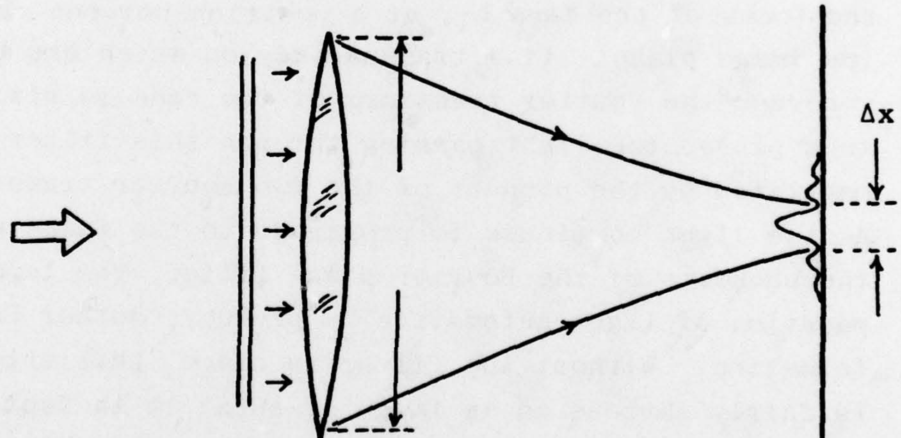


Figure 13b

Figure 13: Diffraction Limitation of the Incoherent Optical Processor

a) Output Plane FOV limitation ≡ Pupil Plane Resolution Limitations

b) Output Plane Resolution limitations ≡ Pupil Plane FOV limitations

6.3 Coherent Processing

There are, of course, coherent optical techniques available which are well suited to computing the cross correlation required for spread spectrum synchronization. These are the more traditional, "holographic" approaches which have been so thoroughly studied since the advent of the laser in the early sixties. One such scheme is illustrated in figure 14. The basic function of the lens is to produce an image of the input $\Delta S(x)$ in the image plane, subject to the usual constraints

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \tag{22}$$

However, common to all optical systems, a Fourier transform of $\Delta S(x)$ will appear in the plane or planes in which the light source is imaged. In this case, with the assumed parallel illumination a Fourier transform will occur at the focus of the lens L_1, at a position between the lens and the image plane. If a transparency on which has been recorded the Fourier transform of the code is placed into this plane, the light passing through this filter will be modulated by the product of the two Fourier transforms. As the light continues to propagate to the image plane from the backface of the Fourier plane filter, the laws of propagation of light automatically produce another Fourier transformation. Without the filter in place, that this must happen is fairly obvious as an image of $\Delta S(x)$ is in fact produced in the image plane. With the filter in place, this additional transformation of a product of transform generates the desired convolution or cross section.*

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*It should be noted that the Fourier transforms and images discussed in the context of coherent systems are in terms of amplitude rather than intensity, unless otherwise stated.

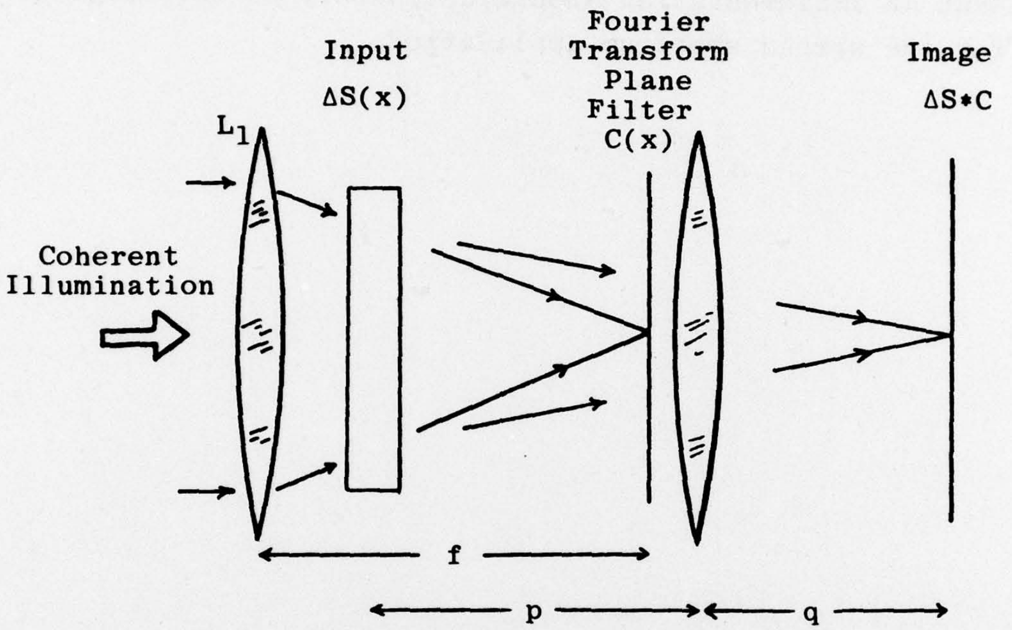

Figure 14: Coherent Optical Processor for producing the cross correlation ΔS*C

As can be seen, this is a relatively straightforward procedure with a number of features to recommend it. Specifically, in contrast to the incoherent approach discussed above, the coherent filters are uniquely defined. Such an implementation should definitely be investigated for the spread spectrum application.

7. RELATIVE MERITS OF THE INCOHERENT VS THE COHERENT APPROACHES

Without attempting to resolve this difficult question in any generality or even to discuss just what are the advantages claimed for each, let us simply note that the spread spectrum task of interest to us here represents an unusual, special case which could well provide us an opportunity for direct experimental comparison. Interestingly, since our desired point response function for the incoherent case is just the binary code itself, the most significant limitation of incoherent processors -- that is, the restriction to positive, real impulse responses -- is not a problem here. In fact, it appears that both the coherent and the incoherent processors can operate with the same filter -- i.e., the Fourier transform of the code. It would seem then that we have here an unusual opportunity to compare the performance of the two competing approaches operating under very similar conditions -- both are attempts to accept the same input $\Delta S(x)$, use the same filter $\tilde{C}(u)$, and obtain the same output $\Delta S * C$.

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(2) William W. Stoner

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